An Intimate Relation with Two Automatic Telescopes for Almost Nine Years

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Abstract

From Oct. 1983 through Dec. 1987 most of the observing capacity of the Boyd–Genet prototype 10-inch APT was devoted to a program of 92 variable stars the output of which was sent to us for analysis. From Nov. 1987 through the present the entire observing capacity of the VU-TSU 16-inch APT has been devoted to a program of 136 mostly magnetically active variables. We review the technical performance of both APTs in terms of malfunctions, down-time, resulting photometric accuracy, phase coverage, and scientific results to date.

1. Introduction.

We want to give a frank account of our experience with two automatic photoelectric telescopes over a time interval of nearly nine years, for the benefit of others just embarking on or contemplating involvement with these remarkable instruments.

We were the principal scientific users of the prototype automatic photoelectric telescope, the so-called Phoenix 10-inch, at the invitation of its developers Louis J. Boyd and Russell M. Genet, from its first night of observation in October 1983 until the last night of calendar year 1987. During these 4.2 years we received differential photometry of a grand total of 92 program stars, 72 of them known or suspected variables of the chromospherically active type.

During that time a 16-inch automatic telescope was acquired with the help of an N.S.F. grant to Vanderbilt University and its continued operation has been funded by N.A.S.A. and N.S.F. grants to Tennessee State University. This VU-TSU 16-inch saw first light in November 1987, has observed variable stars for the 4.7 years between then and the date of this Colloquium, and is still working as we write this paper. At this moment 136 program stars are on its menu, along with 20 UBV standards.

Specifics detailing the operation of these two automatic telescopes have been published elsewhere, references in Table 1, and will not be repeated here. Moreover, the paper by Henry and Hall (1992), presented at the Workshop on Robotic Telescopes in Kilkenny just before this Colloquium, is useful as a companion to this paper. Let us explain, however, that these telescopes do obtain differential magnitudes between a program star and a nearby comparison star and, at the same time, differential magnitudes between a check star and that same comparison star. The sequence of 10-second

Table 1. References pertaining to the 10-inch and the 16-inch.

I.A.P.P.P. Communications	P.A.S.P.
1984 - No. 12, p. 20	1986 - Vol. 98, p. 618
1985 - No. 19, p. 41	1987 - Vol. 99, p. 660
1985 - No. 21, p. 59	1991 - Vol. 103, p. 221
1985 - No. 22, p. 47	
1986 - No. 25, p. 32	
1986 - No. 25, p. 43	Ap. J. Supplement
1988 - No. 33, p. 10	1988 - Vol. 67, p. 439
1990 - No. 42, p. 44	1988 - Vol. 67, p. 453
1990 - No. 42, p. 54	1989 - Vol. 69, p. 141
1991 - No. 45, p. 11	1990 - Vol. 74, p. 225

Table 2. New Variables Discovered with the 10-inch and 16-inch

omi Dra = omi Dra [A]	HD 28591 = V492 Per [A]
eps Hya = eps Hya [A]	HD 31738 = V1198 Ori [A]
33 Psc = BC Psc [B]	HD 43930 = ? [A]
xi UMa = xi UMa [A]	HD 71071 = LU Hya [A]
	HD 80715 = BF Lyn [A]
HR 454 = OP And [A]	HD 90385 = ? [A]
HR 1362 = EK Eri [A]	HD 116204 = BM CVn [A]
HR 1970 = V1197 Ori [B]	HD 136901 = UV CrB [B]
HR 3337 = LO Hya [C]	HD 144515 = ? [A]
HR 4430 = EE UMa [A,B]	HD 152718 = ? [A]
HR 6469 = V819 Her [A,B,C]	HD 155989 = ? [A]
HR 6626 = V826 Her [B]	HD 160952 = ? [A]
HR 6902 = [C]	HD 163621 = ? [A]
HR 6950 = [B]	HD 181219 = ? [C]
HR 7428 = V1817 Cyg [A,B]	HD 181943 = ? [A]
HR 7578 = [A]	HD 191011 = ? [A]
HR 9024 = OU And [A]	HD 191262 = ? [A]
	HD 193891 = ? [A]
HD 1405 = ? [A]	HD 209943 = ? [A]
HD 6286 = ? [A]	HD 212280 = ? [A]
HD 9313 = ? [A]	HD 217188 = AZ Psc [A]
HD 12545 = ? [A]	HD 218153 = KU Peg [A]
HD 19485 = ? [A]	HD 219989 = OT And [C]
HD 19942 = ? [A]	HD 222317 = KT Peg [A]
HD 25893 = V491 Per [A]	

A = spots, B = ellipticity, C = eclipses

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integrations which results in a 'group observation' is K-S-C-V-C-V-C-V-C-S-K, where K = check star, S = sky, C = comparison star, and V = variable or program star. A group observation is accomplished in about six minutes, of which about 75% is spent counting photons, the remaining 25% spent deciding which star to observe next, moving to that star, finding it, verifying its identity, centering it in the diaphragm, and switching filters. Henry and Hall (1992) explain the 'first-to-set-in-the west' rule which the telescope control program uses to assure that the maximum number of program stars on the master menu are observed once each night, this being the optimum observing frequency for these stars most of which vary on time scales generally longer than one day. Moreover, Henry and Hall (1992) explain the function of the 'cloud filter', the procedure by which group observations having a mean differential magnitude uncertain by more than $0^{m}.02$ are not archived, i.e., eliminated. We see later that the cloud filter was recently tightened from $0^{m}.02$ to $0^{m}.01$.

2. Accomplishments

One measure of the performance of these two automatic telescopes is a simple listing of the new variable stars they have discovered. As shown in Table 2, the total to date is 47, of which 16 are of naked-eye brightness, *i.e.*, in the *Yale Bright Star Catalogue.* The official variable star designation is given except for those discovered too recently to have been named. It happens that all 47 vary in brightness by one or more of the same three physical mechanisms: starspots (rotation), the ellipticity effect (tidally distorted shapes), or eclipses. Note that all three mechanisms contribute in HR 6469 = V819 Her.

That is, though, just one measure. Both telescopes have been programmed to observe a large number of stars approximately once each night on as many nights throughout a year as is possible and continuously for as many years as is possible. Most of the program stars are chromospherically active and hence heavily spotted. As a result, their variability is on a variety of time scales (Hall 1992) and the multiple periodicities are a challenge to sort out. Rotation periods are days, weeks, or months; starspots or active regions live for weeks, months, or years; and magnetic cycles of years or decades modulate the mean brightness. These time scales all are long enough that continuous photometry throughout one night is not warranted, and so these automatic telescopes in their one-point-each-night year-after-year mode are proving ideal for the challenge. Examples of spotted stars with photometric coverage approaching or exceeding a decade, much of it with these two telescopes, are V1764 Cyg (Lines *et al.* 1987), σ Gem (Strassmeier *et al.* 1988), V478 Lyr (Hall, Henry, Sowell 1990), HR 1362 (Strassmeier, Hall, Barksdale, Jusick 1990), V1817 Cyg (Hall, Gessner, Lines, Lines 1990), HD 181943 (Hooten and Hall 1990), HK Lac (Oláh, Hall, Henry 1991), EI Eri (Strassmeier 1990), V711 Tau (Henry and Hall 1991), τ Per (Hall *et al.* 1991a), λ And (Hall *et al.* 1991b), V1149 Ori (Hall, Fekel, Henry, Barksdale 1991), BM Cam (in preparation), and DK Dra (in preparation).

Table 3. Problems causing data to be lost or accuracy to be diminished.

problem	effect on data	stars affected	APT	time interval affected
leap year	lost	all	10	1 nt
computer	lost	half	10	Δ t = 180 nts
electronics	< $0^m.05$	bright	10	2 nts
floppies	lost	all	10	9 nts
stuck filter	lost	all B,U	10	3 hrs
dead time	< $0^m.05$	bright	10	Δ t = 485 nts
filter fell out	salvageable	all V	10	Δ t = 28 nts
power supply	$\sigma_{ext} = 0^m.02$	all	10	Δ t = 150 nts
worm gear	$\sigma_{ext} = 0^m.02$	all	16	gradually worse up through 2Q 90
centering	σ_{ext} large	all	16	Δ t = 12 nts
secondary mirror	lost	20%, high k	16	2 quarters
lady bug	lost	all	16	3 nts
$\epsilon = f(T)$	< $0^m.02$	large Δ(B-V)	both	through 2Q 91
aborts	lost	a few	both	throughout

Table 4. Important dates in the history of the two automatic telescopes.

10-inch

12-13 Oct. 1983 was first night of data with the 10-inch.
No data were taken on 29 Feb. 1984, the first leap year.
On 7 Feb. 1985 the 'dead time' problem was corrected.
On 1 July 1985 the yellow filter fell out.
On 1 Aug. 1985 the yellow filter was cemented back into place
~1 Dec. 1985 symptoms of power supply malfunction were first apparent.
On 1 May 1986 the power supply was repaired.
During July, Aug., and Sept. of 1986, the 10-inch was being moved from downtown Phoenix to the top of Mt. Hopkins.
30-31 Dec. 1987 was our last night of data with the 10-inch.

16-inch

12-13 Nov. 1987 was first night of data with the 16-inch
Through 1Q 1988, UBVRI photometry with a GaAs photomultiplier.
BV photometry with a new photomultiplier began with 2Q 1988.
During 3Q 1990, worn worm gear drive replaced with new belt drive system.
Operation with ATIS began with 4Q 1990.
In mid October 1990, transient bug in centering algorithm corrected.
During 2Q 1991, first noticed symptoms of misaligned secondary mirror.
From July 1991 through Feb. 1992, precision photometer installed.
Beginning in March 1992, master menu includes standards, for nightly determination of extinction and transformation.
In mid-June 1992, secondary mirror misalignment corrected.
Operation with $0^m.01$ cloud filter began with 2Q 1992.
Lady bug problem in June 1992.

3. Problems

Table 3 lists all of the problems, other than clouds or daylight or time off for equipment upgrade, which have caused data to be lost or accuracy to be diminished. The second column indicates whether data were lost altogether, or the external error σ_{ext} became larger, or a systematic error was introduced. The third column indicates how many program stars were affected, for example, only the brightest stars, or only stars with a large color difference between variable and comparison, or mostly stars at high declination. The last column indicates the time interval affected. In some cases we give an exact number of nights on which data could have been taken but were not, or were actually taken and then lost, or were actually taken but with diminished accuracy. In other cases we give a time interval Δt during which a problem persisted, noting that many of the nights within Δt were unusable for other reasons.

A detailed account of the problems which affected the 10-inch can be found in Hall, Kirkpatrick, Seufert (1986) and Boyd, Genet, Hall, Busby, Henry (1990). Of the remaining problems, which have affected the 16-inch, Henry and Hall (1992) have described in detail the worn worm gear problem, the centering problem, and the temperature-dependent transformation coefficient problem, but not the secondary mirror problem or the lady bug problem. The first of these was simple but nasty. A loose screw caused the secondary mirror to slip, ruin the telescope alignment, and foul up the acquisition and centering process. The telescope failed to locate a number of stars, mostly at higher declinations, which should have been no problem. The second of these affected three nights in June 1992 when a lady bug (or maybe three different lady bugs) sat on the infrared LED which serves as a limit switch to signal that the telescope has reached the horizontal 'home' position. This made the telescope control computer think the night was over and turn off power to all instruments. The last problem in the list, the aborts, has affected both telescopes intermittently throughout the nine years. An abort occurs when the telescope executes its outward spiral search for the next star to be observed and cannot find it within 15 arcminutes of the starting point. The problem, other than a cloud in front of the star, usually proves to be an incorrect right ascension or declination, a nearby star of comparable brightness which we had not recognized, or a 'hunt magnitude' (the nominal brightness used to verify a star's identity during the acquisition stage) set too bright.

The number of group observations which were actually made and then lost or which could have been made but were not, when compared to the total number made successfully, amounts to a loss of only 10% or so. This is minimal compared to the three months of down time every summer, the monsoon season in southern Arizona, during which time we also perform most of the necessary repair, maintenance, and upgrade work.

Table 4 gives a list of dates and time intervals during which telescope operation began or ended, problems developed and ended, equipment upgrades were effected, observing or data reduction procedures were changed, etc.

Table 5. History of accuracy with the two automatic telescopes

APT	σ_{int}	σ_{ext}	situation
10	$0^m\!.005$	$0^m\!.010$	before power supply problem
10	–	0.016	during power supply problem
10	–	0.008	after power supply problem, on Mt. Hopkins
16	–	0.007	first year of operation
16	0.010	0.016	just before replacing worm gear drive
16	0.005	0.008	after installing belt drive
16	0.003	0.005	after precision photometer, nightly k, constant ϵ
16	0.003	0.003	best photometric nights only

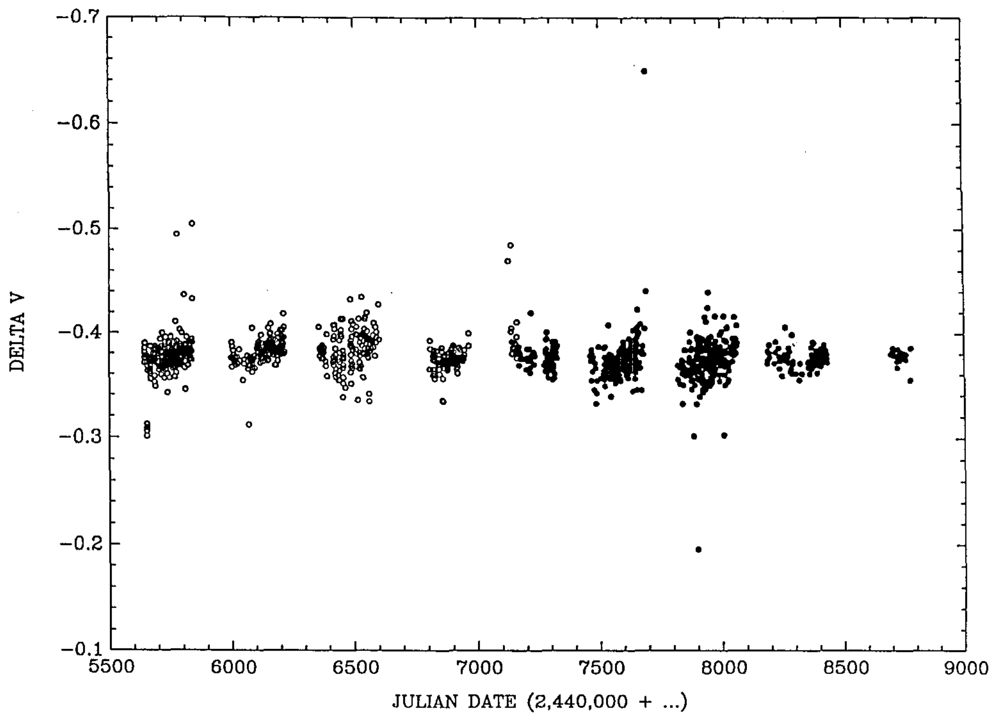

Figure 1. Each point is a group mean differential magnitude of the star pair 27 and 28 LMi, open circles are from the 10-inch, filled circles from the 16-inch. Note the 1-month overlap in late 1987. The rms deviation from the 9-year mean is σ_{ext}. A periodicity close to the tropical year shows up in these data, a consequence of the temperature-dependent transformation coefficient, with the large color difference between 27 and 28 LMi making this star pair particularly vulnerable. The last bunch of points as shown has not yet been passed through the 'second filter' but, after filtering, would show $\sigma_{ext} = 0^m\!.003$.

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4. History of the photometric accuracy

Table 5 is a summary of the evolution of the photometric accuracy achieved by both the 10-inch and the 16-inch. As explained by Hall, Kirkpatrick, and Seufert (1986), σ_{int} is simply the standard error of the mean of the three differential magnitudes within each group observation, calculated from the standard deviation of those three from the mean. On the other hand, σ_{ext} is the standard deviation of all group means from an average over some long interval of time, in the case of a program star which is constant, or from a calculated light curve fit in the case of a periodic variable.

Note that σ_{ext} on the 10-inch began at $0^{m}_{\cdot}010$, worsened during the power supply malfunction, and recovered after its repair. Similarly, σ_{ext} on the 16-inch began at $0^{m}_{\cdot}007$, worsened as the worm gear wore, recovered after its replacement, was improved to an impressive $0^{m}_{\cdot}005$ by the precision photometer and nightly observation of standards, and improved more still — to the theoretical limit — when a 'second filter' was used to discard data from all but the first-class photometric nights, as judged by the photometry of the standards in the all-sky mode.

Figure 1 illustrates the content of Table 5 in graphical form. Each point is a group mean of the star pair 27 and 28 LMi, with the latter considered the variable. Open circles are from the 10-inch, filled circles from the 16-inch. Note the 1-month overlap in late 1987. The rms deviation from the 9-year mean is σ_{ext}. A periodicity close to the tropical year (376 ± 2 days) shows up in these data. As Henry and Hall (1992) show, this is surely a consequence of the temperature-dependent transformation coefficient, with the large color difference between 27 and 28 LMi making this star pair particularly vulnerable. The last bunch of points as shown in Figure 1 has not yet been passed through the 'second filter' described in the paragraph above but, after filtering, would show $\sigma_{ext} = 0^{m}_{\cdot}003$.

Acknowledgements

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Discussion

W. Lockwood: *The APT and manual telescopes have the same duty cycle ~ 75%. But the APT centres better and moves faster than our manually-operated 21-inch telescope. Yet we get the same precision, ~ 0.003 mag rms. Evidently, therefore, time-dependent extinction and imprecise centering are not the causes of low precision, to within ~0.003 mag.*

Hall: It seems as if we both are at our 'theoretical limit', i.e., the precision limited by the combination of photon noise and scintillation.

W. Tobin: *Are the discovery times for problems that you showed really such that you need to be apologetic about them? I suspect it can take just as long and in many cases longer for such discoveries to be made with manual operations.*

Hall: You are probably correct, and I thank you for your kind perspective. Let me add something. In the beginning, when we received our data in batches on a quarterly basis, we were necessarily limited to discovery on a time scale of months. Now we can receive data on a morning-after basis and normally do examine it on the spot, making for discovery on a time scale of days, at least for the more obvious problems. Let me add, in conclusion, that our APT operation probably encounters fewer problems than would have been so with manual operation. That is because an APT, the ultimate dedicated telescope, experiences the absolute minimum number of equipment changes, modifications, human interference, etc.

R.L. Hawkins: *Can the APT system get data points for the variable spaced by two minutes or less?*

Hall: Yes, the system can be programmed to do so, but since I work on long period variables, I have not done so.